FREE RESPONSE OF PIEZOELECTRIC CRYSTALS IN SERIES AND IN PARALLEL

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ABSTRACT. The free response is considered of piezoelectric crystals (lithium niobate) with various polarities (including longitudinal only, shear only, and combined longitudinal and shear), which are stacked (mechanically and electrically in series) or are parallel (electrically parallel and mechanically uncoupled). Measurements of impedance magnitude from an impedance analyzer are compared with results from PSPICE simulations using a Mason model. These PSPICE models may serve as the basis for designing physical transducers from crystal stacks.

INTRODUCTION

Stacked piezoelectric elements have been used for some time to obtain large displacements, such as for lithotriptors or ultrasonic welders [1]. A stack combining longitudinal and crossed shear layers has been employed for static force measurement [2]. In the present work, the concept for a multi-mode transducer is based upon stacked crystals, each of which has a piezoelectric response to both longitudinal and shear waves, and which utilizes polarization cancellation to separate the two modes.

It is common to use electrical circuit equivalent models, such as the KLM or Mason models, as a tool for transducer design [3]. As a preliminary process to the development of a multi-mode transducer, a Mason model, which is implemented using the electric circuit simulation software PSPICE [4], is used to simulate the free response of piezoelectric crystals in series and in parallel.

TRANSDUCER CONCEPT

Schematic representations of the cross-section of piezoelectric crystals with different voltages applied are presented in Fig. 1. In the figure, electrodes are indicated by a darker gray color, while the piezoelectric polarization is indicated by an arrow. The zero-voltage state is indicated by a dashed line. The figure indicates that with a positive applied voltage, a longitudinal polarized crystal expands, a shear polarized crystal shifts to the right, and the mixed mode crystal both expands and shifts to the right. Under a negative applied voltage, the motion is opposite; the longitudinal crystal contracts, the shear crystal shifts to the left, and the mixed mode crystal both contracts and shifts left.

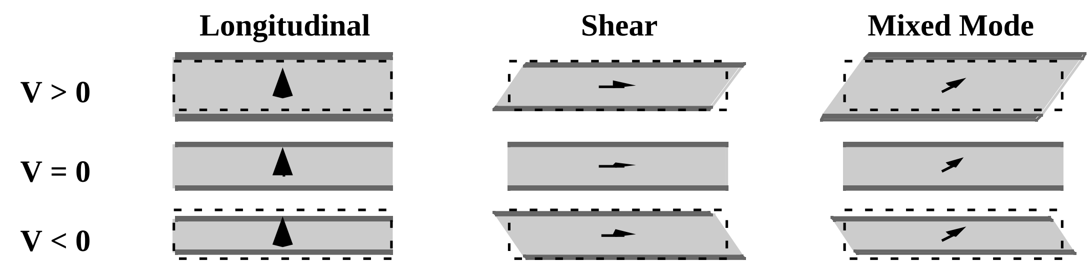

FIGURE 1. Schematic representation of free crystals with different polarizations, responding to applied voltages.

Because longitudinal and shear wave modes are orthogonal, they are mechanically independent. This mechanical separation of modes in a mixed-mode crystal is illustrated in Fig. 2. The two modes are modeled as mechanically separate crystals, which are electrically in parallel because they share the same physical electrodes. The PSPICE model of a mixed mode crystal will be based on this conceptual representation.

Figures 3 and 4 illustrate the behavior of piezoelectric crystals in a stacked configuration, both mechanically and electrically in series. In Fig. 3, crystals of like polarization are stacked with their polarizations parallel, and the same voltage is applied across both crystals in the stack. That is, the voltages are applied *symmetrically*. Under applied voltage, each crystal responds according to its polarization, and because these are parallel, the motion of the stack faces is double that of the individual crystals. In Fig. 4, the same crystal stacking is shown, but the voltages are applied *anti-symmetrically*, with the voltages applied to top and bottom crystals being the negative of each other. In this case, the relative motions from the two crystals are opposite each other, and thus, cancel each other. It is the constructive and destructive summation of responses suggested by Figs. 3 and 4 which is the conceptual basis for the proposed dual-mode transducer.

Consider the stack configuration depicted in Fig. 5. Two mixed mode crystals are stacked with their shear polarities parallel, and their longitudinal polarities anti-parallel. Thus, in a symmetrical voltage arrangement, the shear wave motions are doubled while the longitudinal wave motions are cancelled. Similarly, in an anti-symmetrical voltage arrangement, the longitudinal wave motions are doubled while the shear wave motions are cancelled. One can conceivably construct a transducer using this stack configuration, which can produce only shear waves when driven symmetrically, and produce only longitudinal waves when driven anti-symmetrically. One can also conceivably separate longitudinal and shear wave components from a received wave by creating symmetric and anti-symmetric signals from the signals received separately from the top and bottom crystals of such a transducer.

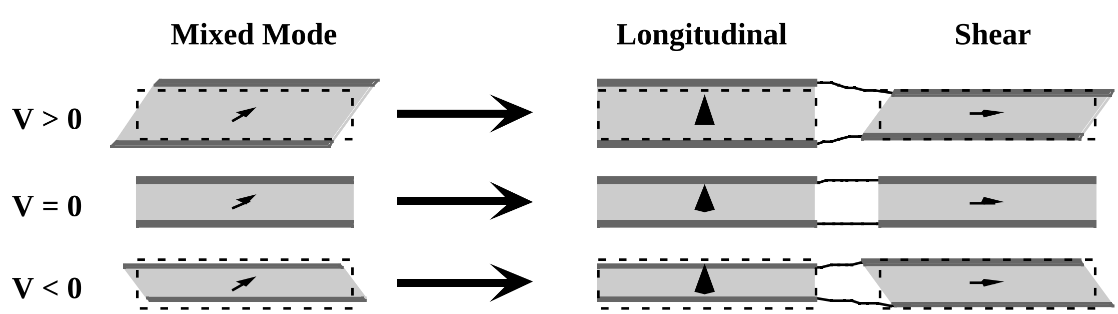

FIGURE 2. Schematic representation of mixed polarization crystal, indicating the mechanical independence of the two modes, modeled as a longitudinal polarized crystal connected electrically in parallel with a shear polarized crystal.

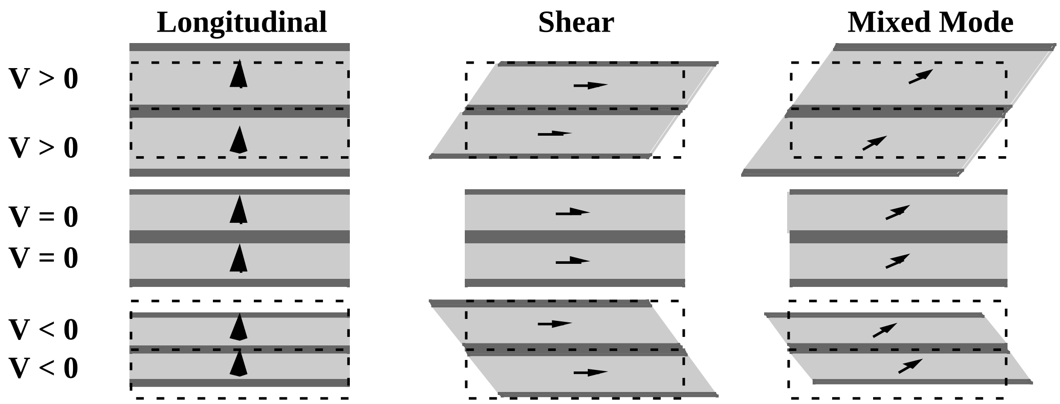

FIGURE 3. Schematic representation of stacked crystals with parallel polarization, driven symmetrically, that us with the same voltage applied across both crystals. The crystals are both mechanically and electrically in series. Relative motions of the two crystals are in same direction, and thus, double the total response.

CRYSTALS SELECTED FOR STUDY

Commercially available lithium niobate crystals having the desired mixed-mode properties were used in this study [5]. A mixed-mode, 10° rotated Y-cut lithium niobate crystal has nearly identical piezoelectric coupling factor for longitudinal waves and for shear waves. Also, because the wave speeds have a ratio of approximately 3/2 for that cut, the first longitudinal harmonic and the second shear harmonic fall at approximately the same frequency, which could be a convenient feature for designing a dual-mode transducer.

For this study, three crystals each were obtained having longitudinal-only response (36° Y-cut) with fundamental resonance at 4.0 MHz, and shear-only response (41° X-cut) with fundamental resonance at 2.5 MHz. Two crystals were obtained having the mixed mode response (10° Y-cut). For these crystals, the longitudinal resonance was at 4.15 MHz and the shear resonance was at 2.5 MHz. Table 1 presents the density, wave speeds and piezoelectric coupling factors for each of these crystal orientations.

The impedance magnitude was measured using an impedance analyzer for each of these crystals separately, and also for various series and parallel combinations.

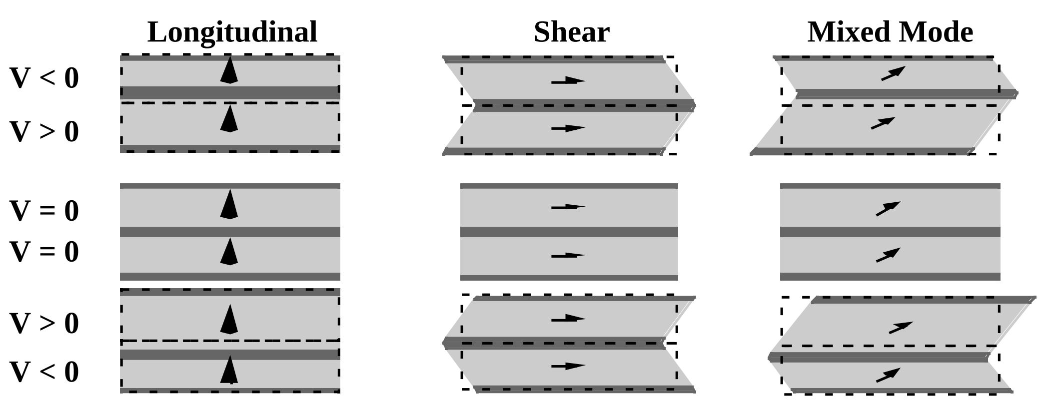

FIGURE 4. Schematic representation of stacked crystals with parallel polarization, driven anti-symmetrically. Crystals are both mechanically and electrically in series. Relative motions from two crystals are in opposite directions, and thus, cancel.

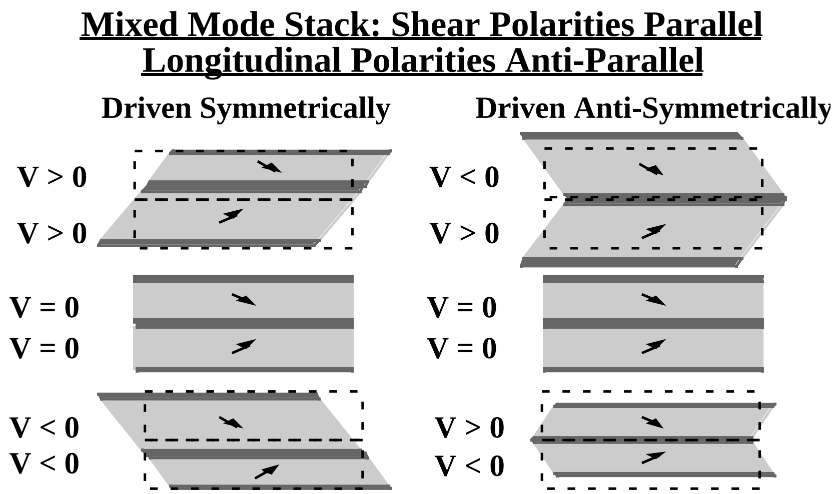

FIGURE 5. Schematic representation of stacked mixed mode crystals with parallel shear polarization and anti-parallel longitudinal polarization. When driven symmetrically, shear motion, but no longitudinal motion, is produced. When driven anti-symmetrically, longitudinal motion, but no shear motion, is produced.

MASON MODEL IN PSPICE

The PSPICE implementation of the Mason equivalent circuit for an ultrasonic transducer is shown in Fig. 6. The mechanical resonator is modeled as a lossy delay line, while the piezoelectric coupling into the electrical port is accomplished by a transformer and capacitors. Values for the capacitances, the number of turns in the transformer, and the various characteristics of the delay line are assigned values based upon the physical properties of the piezoelectric, in this case, lithium niobate [3]. To simulate the free response of a piezoelectric crystal, the mechanical ports were each terminated by resistors with values to represent air. A short impulse was introduced at the electrical port, and the electrical response was monitored. The frequency spectrum of this impulse response shows the resonances of the crystal similarly to the measured impedance magnitude.

RESULTS

The response from a 4 MHz longitudinal polarized crystal is presented in Fig. 7. In the upper panel is the impulse response simulated using PSPICE. The fundamental resonance (labeled L0) and the first harmonic (labeled L1) are clearly seen. In the lower panel are the measured impedance magnitudes of three longitudinal lithium niobate crystals. In addition to the L0 and L1 resonances are some low frequency lateral mode resonances.

TABLE 1. Properties of the lithium niobate crystals used in this study.

	36° Rotated Y-cut	**41° Rotated X-cut**	**10° Rotated Y-cut**
Density	4.63 g/cm^3	4.63 g/cm^3	4.63 g/cm^3
Longitudinal wave speed	7.340 mm/µs	–	7.063 mm/µs
Longitudinal coupling factor	0.485	–	0.472
Shear wave speed	–	4.795 mm/µs	4.271 mm/µs
Shear coupling factor	–	0.684	0.436

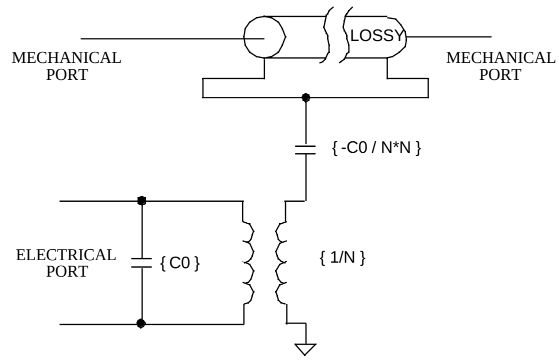

FIGURE 6. PSPICE representation of a Mason equivalent circuit for a resonant crystal.

In Fig. 8 are the results for 2.5 MHz shear polarized crystals. The PSPICE model clearly shows the fundamental (S0) and the first two harmonic resonances (S1 and S2). The measured impedances from the three shear crystals exhibit these same three resonances.

The response from a mixed mode crystal is presented in Fig. 9. The model data show longitudinal resonances (L0, L1) and shear resonances (S0, S1, S2). The measured imepedance magnitude from two mixed-mode crystals shows these same resonances, along with some low frequency spurious modes. The two nearby resonances, (L1, S2), which are slightly separated in the model, merge into a single response from the actual crystals.

As a test of the conceptual model in Fig. 2, the impedance magnitude was measured of a longitudinal crystal and a shear crystal connected electrically in parallel, but otherwise free of each other. Fig. 10 presents the impedance for each crystal individually (broken

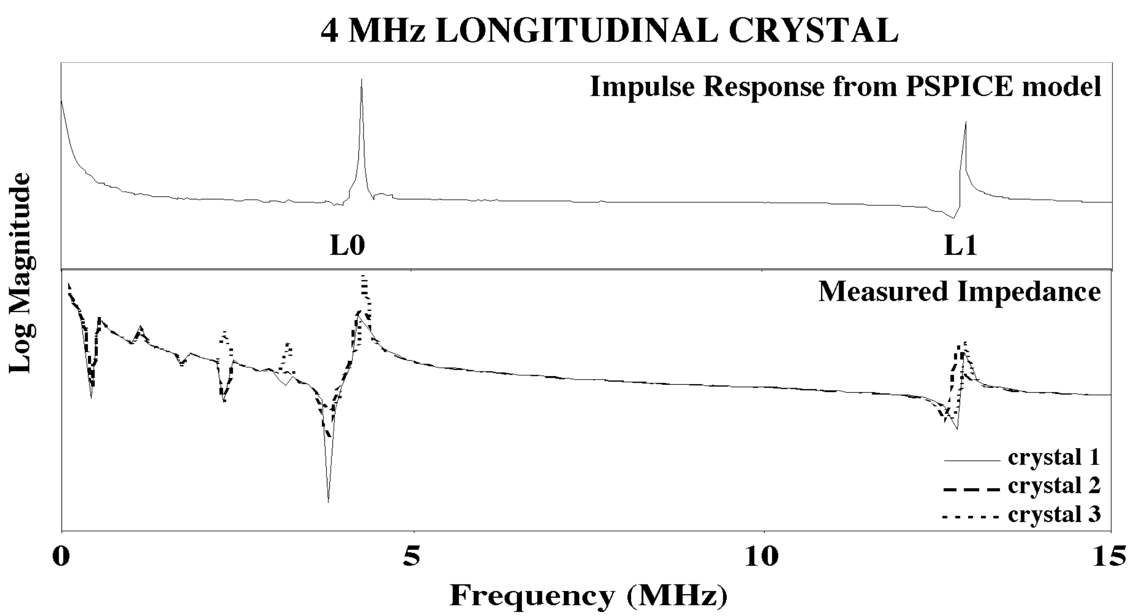

FIGURE 7. Free response of a single, longitudinal polarized crystal.

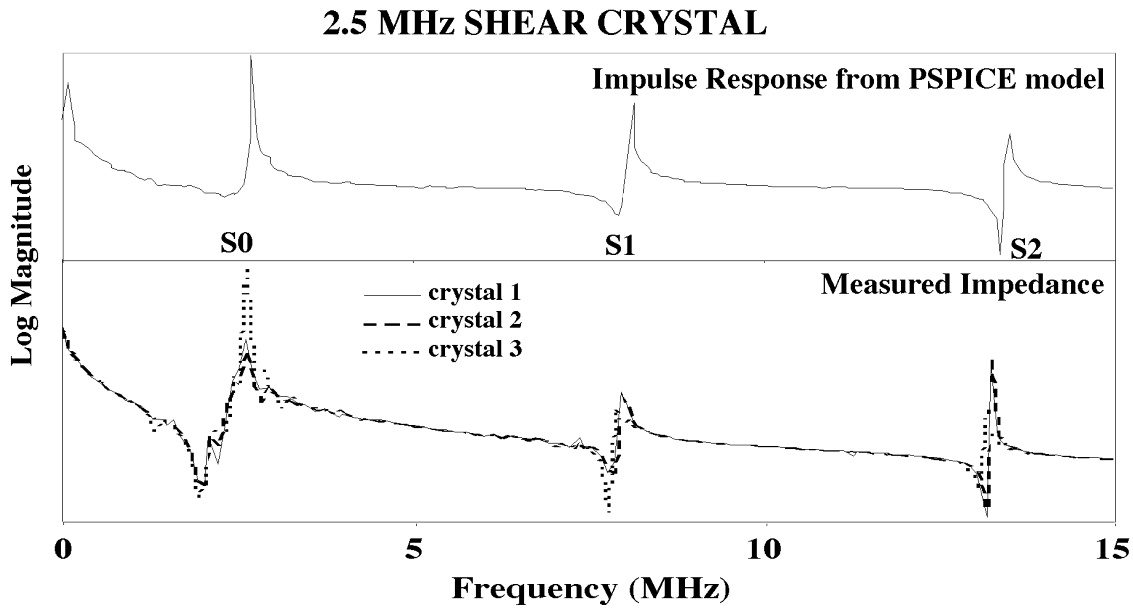

FIGURE 8. Free response of a single, shear polarized crystal.

curves) and for the electrically parallel combination (solid curve). The parallel impedance shows the same combined resonance structure as observed in Fig. 9.

Results obtained for crystal in series are presented in Figs. 11-13. In these figures, the results are plotted in pairs; data for top and bottom polarities parallel are plotted with a solid line, while data for polarities anti-parallel are presented with a broken line. The crystals were bonded using a thin wax bond.

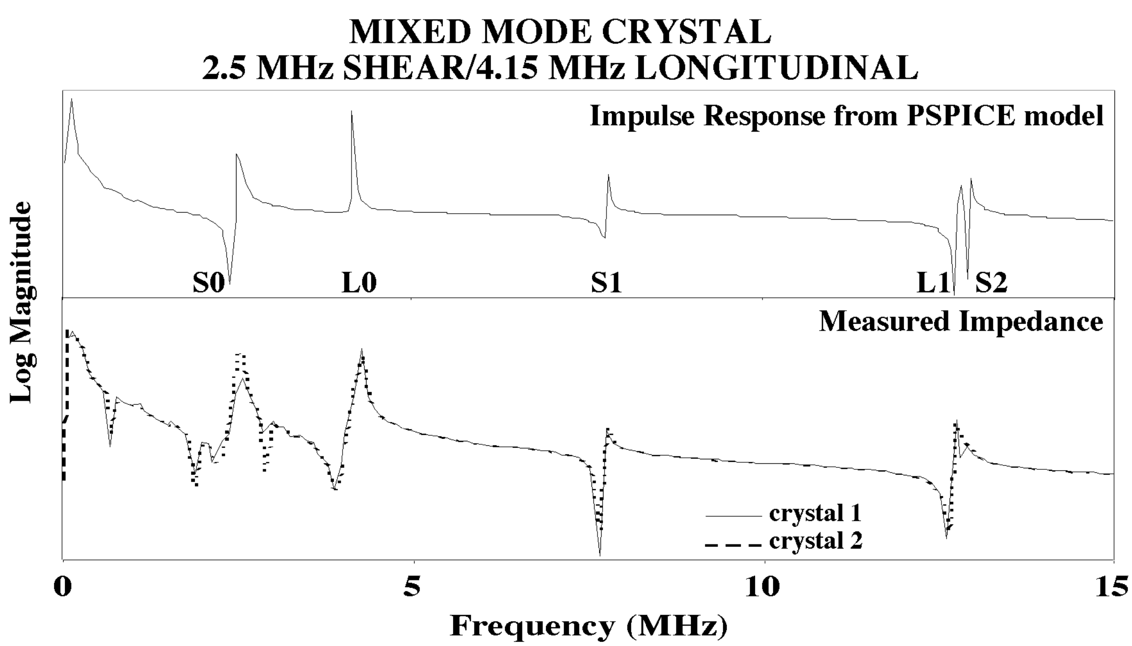

FIGURE 9. Free response of a single, mixed mode longitudinal and shear polarized crystal.

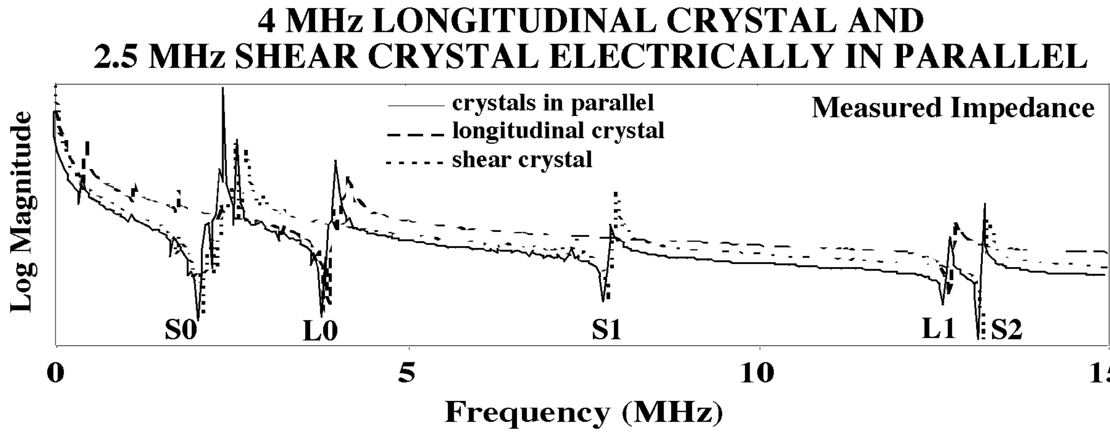

FIGURE 10. Impedance magnitude of a single longitudinal crystal and a single shear polarized crystal, and the same two crystals connected in parallel.

In Figs. 11 and 12, the longitudinal and shear stacks with parallel polarity show the expected halving of fundamental resonance frequency, resulting from the effective doubling of resonator thickness. When anti-parallel, the same crystals each oscillate with the single crystal resonances, but out of phase by 180°. The measured stack impedances for anti-parallel crystals agree with the model results, however the results for parallel crystals are quite different from the model. The longitudinal stack shows a small resonance at the halved fundamental, but no significant behavior at higher frequencies.

For the mixed mode crystals, the measured impedances in Fig. 13 seem consistent with a parallel combination of the impedances from Figs. 11 and 12, which suggests that the difference is not a measurement error. The modeled responses in Fig. 13 bear little similarity to either the measured impedances or the model results in Figs. 11 and 12.

CONCLUSION

The PSPICE model for mixed mode crystals was developed and demonstrated for free crystals and crystals electrically in parallel. For series crystals, there are differences between the model results and measured impedances. It is speculated that these arise from the wax bond in the measured stacks, which was not included in the model. When these differences are resolved, the models can then serve as basis for design of a dual mode transducer.

ACKNOWLEDGMENT

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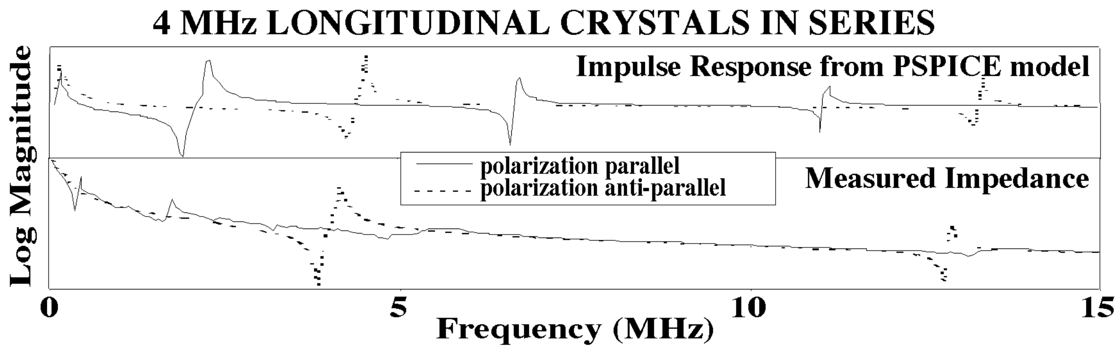

FIGURE 11. Free response of longitudinal polarized crystals in series.

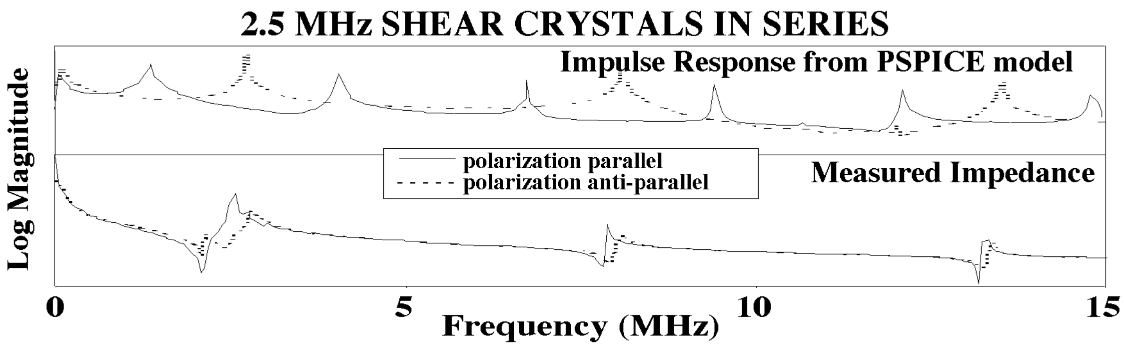

FIGURE 12. Free response of shear polarized crystals in series.

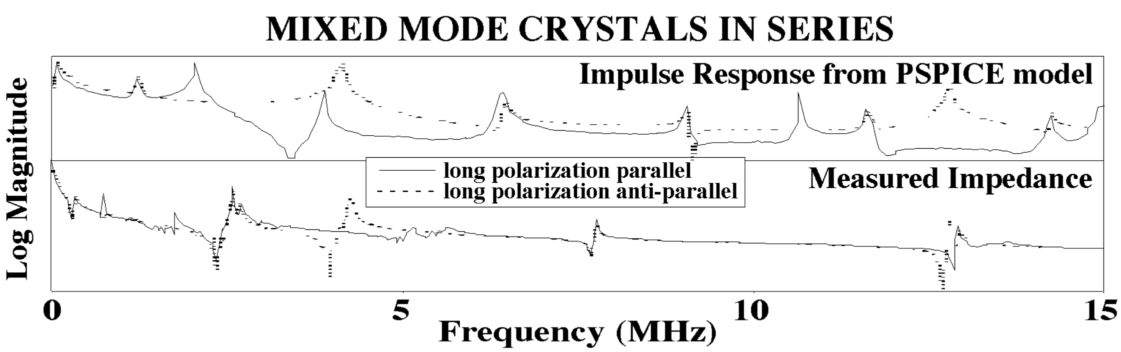

FIGURE 13. Free response of mixed mode crystals in series.

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